Gamma Radiation Influence on Thermoelectric Powered Wireless Sensors for Dry-Cask Storage

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***Abstract*- This paper describes using a thermoelectric generator (TEG) to power wireless sensors to monitor spent nuclear fuel during dry-cask storage. This work focuses on testing the wireless sensor circuitry in a gamma radiation environment. A bismuth telluride TEG (HZ-14), DC/DC converter (Linear Technology LTC 3108EDE), and transceiver (EmbedRF) were irradiated at the Wisconsin Institute for Medical Research (WIMR) using a ^{60}Co gamma source with an exposure rate of 170.3 R/min. The thermoelectric voltage and DC/DC converter output voltage was measured before, during, and after gamma radiation using the computer program LabVIEW. A receiver (EmbedRF) with the computer program EmbedRF Desktop Pro recorded the signal count number and relative source strength indicator before, during, and after gamma radiation. It is a goal to understand if the electronics can function properly under gamma radiation. From this analysis it can be determined if the electronic components need to be properly shielded or if radiation hardened devices have been used.**

Keywords- Dry-Cask; Gamma; Thermoelectric; Wireless Sensor

I. INTRODUCTION

A major concern with nuclear energy is the safe storage of the spent nuclear fuel before final disposal. After the nuclear fuel is removed from the reactor, the fuel needs to be placed into storage. Initially there are water pool storage systems, followed by dry-cask storage systems. Water pool spent fuel storage occurs on site, and is only a temporary storage location. After a certain period of time (at least 5 years), the fuel assemblies can be placed into dry-cask storage [1, 2]. The service life of these dry-cask facilities is typically 50 years [1]. For this study the particular system of interest is the horizontal configuration (Fig. 1). This design contains two major components; the dry storage container (DSC) and the horizontal storage module (HSM). The DSC is a stainless steel cylinder that holds the spent fuel assemblies [3]. The DSC is then placed into the HSM. The HSM is a reinforced concrete building that provides radiation shielding. The HSM has air inlet and outlet vents which cool the DSC through natural convection [3].

Fig. 1 Horizontal Dry-Cask Storage Facility for Spent Nuclear Fuel [6]

There are 18,000 metric tons of uranium currently in dry-cask storage, and this value will continue to increase [4]. The Nuclear Regulatory Commission (NRC) has stated that there are several high priority areas of concern for dry-cask storage to assure long term integrity [4]:

- Stress corrosion cracking of stainless steel canister body and welds in marine atmosphere
- Degradation of cask bolts
- Effects of fuel pellet swelling and fuel rod pressurization on cladding stress
- More realistic thermal model calculations
- Effects of residual moisture after canister drying
- In-service monitoring methods for dry storage systems

It has been determined that stress corrosion cracking can occur on canister materials under laboratory conditions [5]. The salts in the air, surface temperature of the canister (DSC) and humidity influence corrosion. However, a current concern is that the environmental conditions within the dry-cask are unknown [5]. The use of wireless sensors would be beneficial in this regard, particularly addressing priority Areas 1 and 6. For instance, the sensors could broadcast surface temperature information by using thermocouples attached to the surface of the canister and measure the humidity inside the dry-cask. These data then can be used to determine if the canister is in a regime that risks stress corrosion cracking. Wireless sensors have the possibility of monitoring the dry-cask throughout its service life. This information could also be used to allow for extending the service life of the dry-cask.

One issue with sensors and transmitters is that these pieces of equipment require a power source. Many sensors use a chemical source, such as a chemical battery, for a power source. A major drawback with chemical sources is that the power source periodically needs to be replaced, refueled, or recharged. In dry-cask storage it is not an option to replace the power source once the DSC is inside the HSM. The decay heat of the spent fuel can be converted into electricity for the wireless sensors by using a thermoelectric generator (TEG) [7]. A potential issue regarding performance and degradation of the sensors is the elevated temperatures and radiation levels within the dry-cask. During the service life of the dry-cask, the TEG and electronics will be exposed to fast neutrons and gamma rays [7]. Many researchers have investigated the behavior of DC/DC converters under gamma radiation exposure [8, 9, 10]. Many devices lost voltage regulation during exposure, while a few were unaffected by the gamma radiation [8, 10].

In this work we present a concept for a thermoelectric powered wireless sensor for the purpose of monitoring spent nuclear fuel. This research focuses on understanding if this gamma radiation will adversely influence any of the sensor components, TEG, DC/DC converter, and transceiver. There are three objectives to this research: first study the effects of gamma radiation on the thermoelectric voltage, second study the effects of gamma radiation on the DC/DC converter output voltage, and third evaluate if the gamma radiation causes signal noise in the transceiver transmission signal, as seen in Fig. 2. It may be necessary to use radiation hardened electronics or properly shield the devices.

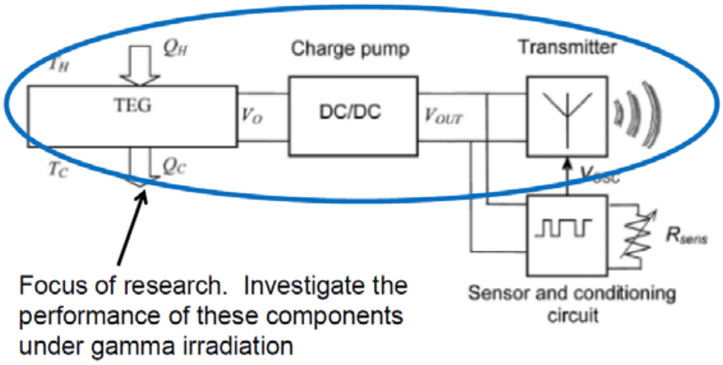

Fig. 2 Electronics required for a thermoelectric powered wireless sensor [11]

II. EXPERIMENT SETUP

The influence of gamma radiation on the thermoelectric voltage, DC/DC converter output voltage, signal count number and relative signal strength indicator (RSSI) were investigated at the Wisconsin Institute for Medical Research (WIMR), which uses a ^{60}Co gamma source. The maximum obtainable exposure rate is 170.3 R/min. From inspection of Table I, this exposure rate corresponds to an exposure rate past the service life of the dry-cask (50 years) [1].

TABLE I GAMMA EXPOSURE RATE DURING DRY-CASK STORAGE

Year During Storage	Exposure Rate (R/min)
0	2636
5	1490
10	1167
15	1000
20	876
30	684
40	539
45	478
50	425
70	266
100	133

The exposure rate ($\dot{X}$) was calculated using the following equation:

$$\text{Exposure Rate} = 0.0659\Sigma E_i \varphi_i \mu_i \ \{\text{mR/hr}\} \ [12]$$

Origen-Arp provided an 18 energy group gamma source strength spectrum. Based on the physical size of the DSC, an estimate of the gamma flux can be calculated. From the average energy of each group (E_i), the gamma flux for each energy group (φ_i), and mass energy absorption coefficient of air for each energy group (μ_i) the exposure rate for each group can be determined [13]. The exposure rate for each energy group was summed up over the 18 energy group spectrum to yield the total exposure rate.

A transceiver (EmbedRf) was powered by a TEG (HZ-14) and DC/DC converter (Linear Technology 1582B), as shown in Fig. 2 and Fig. 3. The DC/DC converter stepped up the thermoelectric voltage to 3.3 V [14].

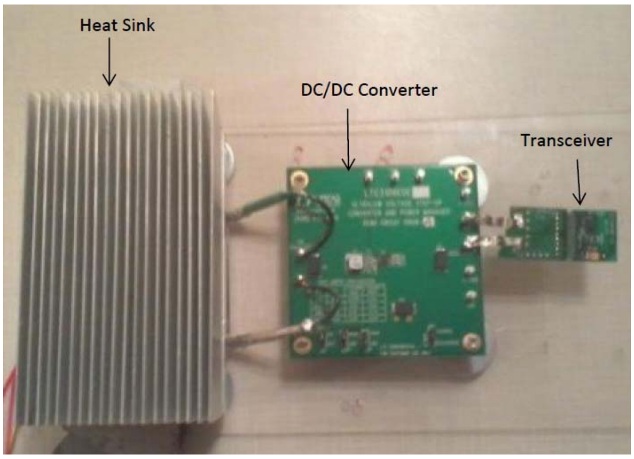

Fig. 3 System components investigated under gamma irradiation (thermoelectric under heat sink)

The transceiver requires an operating voltage between 2.0-3.6 V and broadcasts at frequency of 915 MHz [15]. The TEG was sandwiched between two ceramic plates (Al_2O_3). These ceramic plates were purchased with the TEG from the Hi-Z company [16]. One of the ceramic plates is between the alumina heat sink and TEG, in order to keep the heat sink and the TEG electrically isolated from each other. The purpose of the heat sink is to generate a large temperature difference across the TEG, which will maximize the thermoelectric voltage produced. Details of the alumina heat sink used in this experiment are shown in Fig. 4. On the other ceramic plate there is a 120 V, 10 W/in^2, silicon rubber heater epoxied to it. A type-k thermocouple was epoxied to the ceramic plate to monitor the temperature. The heat sink, TEG, and DC/DC converter were mounted to a 5 in x 10 in x 0.125 in piece of Plexiglas. This Plexiglas plate was mounted to a wooden stand to keep the components off the ground and aligned in a vertical orientation. The circuit and wooden stand were placed on an adjustable track and platform at WIMR. The platform and track centred the circuit in the gamma radiation field.

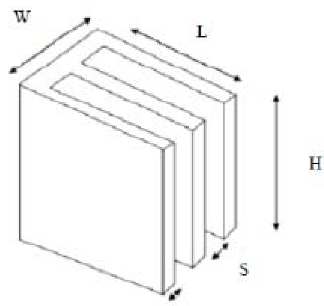

Fig. 4 Heat sink used. Fin thickness (t) 1.1mm, fin spacing (S) 3mm, fin length (L) 44.45mm, fin height (H) 114.3mm, base width (W) 65.09mm, and base thickness 12.7mm

To measure, control, and record the temperature of the plate the computer program LabVIEW was used. The temperature of the hot side of the TEG was set to 58 °C. This temperature corresponds to the surface temperature of the canister after 70 years of dry-cask storage. This surface temperature is large enough for the transmitter to broadcast a signal at a transmission power of 5 dBm and one second broadcast period. The temperature of the plate was controlled by choosing the frequency factor, duty cycle and PID values. The silicon rubber heater was wired to a solid state relay. The relay turned the heater on and off in order to maintain the proper plate temperature. The thermocouples and relays were connected to a NI SCB-68 connector block DAQ device. The SCB-68 connector block was connected to a PCI-6023E card in the desktop computer. The temperature of the plate was recorded every two seconds. In addition, the thermoelectric voltage and DC/DC converter voltage was measured using LabVIEW. LabVIEW saved the date, time, elapsed time, plate temperature, thermoelectric voltage, and DC/DC converter voltage to an excel file.

The transceivers were programmed using EmbedRF Desktop Pro. In this program the transmitter/receiver id, network id, transmission interval, and transmission power were selected. The EmbedRF program has an option to allow the incoming broadcast data to be saved to a text file. For this experiment the transmitter only sent the time, date, RSSI (relative signal strength indicator), and counter number. The transmitter was set to broadcast at the maximum transmission power of 5 dBm and the transmission period was set to one second. The receiver was secured to the back wall of the vault behind the gamma source (The vault is the room where the gamma source is located). The receiver was connected to a desktop computer through a USB cord. The computer was located in room outside the vault. The system was allowed 10 minutes to warm up before collecting transmission data. After this 10 minute warm up period, the transmission data (time, data, RSSI, and count number) were collected for 45 minutes without any radiation. After this 45 minute collection period, the ^{60}Co gamma source was turned on. Once again the transmission data and voltages were collected for 45 minutes during gamma irradiation. After this 45 minute period the gamma source was turned off. Data were collected for an additional six-minute period after irradiation in order to determine if the measurements returned to their pre-irradiation values. As seen in Table II, there was no change in the k-thermocouple temperature measurement of the plate before, during, and after gamma irradiation.

TABLE II PLATE TEMPERATURE COMPARISONS FOR DIFFERENT CASES

	No radiation	60Co radiation ($\dot{X}$=170.R/min)	End no radiation
Average Plate Temperature (°C)	58.179	57.903	58.316
Standard Deviation of Plate Temperature (°C)	1.754	1.640	1.503

III. RESULTS

The quantities of interest under gamma radiation are: the thermoelectric voltage, the DC/DC converter, RSSI, and signal counter number (determines signal noise). Fig. 5 shows the difference between the thermoelectric voltage before and during gamma irradiation.

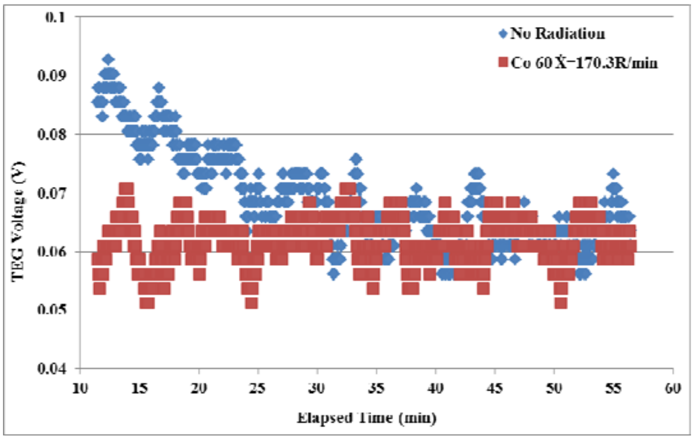

Fig. 5 Comparison of thermoelectric voltage before and during gamma irradiation vs. elapsed time

A possible reason for the thermoelectric voltage to be higher at the start could be due to the fact it took the heater longer than 10 minutes to reach a steady state temperature of 58 °C. The gamma source is located in a vault. Once the transceiver circuit was properly positioned in the gamma source window, the vault door was closed and no one entered the room until the experiment was finished. After this the heater was allowed 10 minutes to warm up. After this period the transmission data and voltage measurements were collected for 45 minutes without radiation. After 45 minutes the operator turned on the gamma source to collect data during radiation. After irradiation data were collected again for six minutes. Hence the vault was never opened and data were continuously collected over a 96 minute period (45 minutes no radiation, 45 minutes with radiation, 6 minutes after radiation). In Fig. 5 the thermoelectric voltage with radiation line (red) starts where the thermoelectric voltage with no radiation line (blue) ends. The lines were graphed over the top of each other to demonstrate any differences in the thermoelectric voltage. Hence, if one looks at the data after 25 minutes there is good agreement between the radiation and no radiation thermoelectric voltage values. So it is believed that the gamma radiation does not influence the thermoelectric voltage. The discrepancies in the data are from the heater taking longer than 10 minutes to reach a steady state temperature.

The gamma radiation influences the DC/DC converter output voltage, as shown in Fig. 6. Without radiation the DC/DC converter voltage stayed at a constant value of 3.3 V. During the gamma radiation exposure the DC/DC converter voltage decreased and oscillated by 0.7 V. There was a loss of output voltage regulation. During the 45 minute collection period, the minimum DC/DC converter output voltage was 2.5 V. The transceiver from EmbedRF requires an operating voltage between 2.0-3.6 V [15]. If the voltage drops below 2.0 V the transceiver will not operate. During irradiation, the DC/DC converter output voltage occasionally reached a value of 3.3 V. This behavior can be explained by the design of the gamma source. As a safety design feature the gamma source has a 20 minute operating time window. Hence, after 20 minutes the operator is required to reset the machine. As seen in Fig. 6 at an elapsed time of 30 minutes and 50 minutes when the gamma radiation temporally stopped and the DC/DC converter output voltage returned to its original value of 3.3 V.

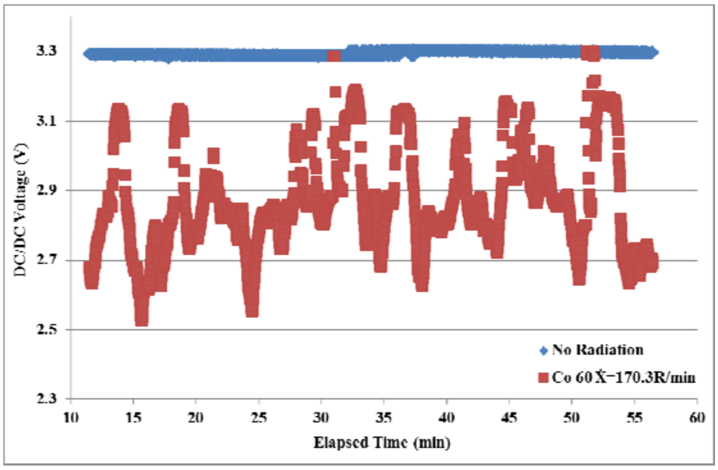

Fig. 6 Comparison of DC/DC converter output voltage before and during gamma irradiation vs. elapsed time

Fig. 7 and Fig. 8 show the thermoelectric voltage and DC/DC converter output voltage after gamma radiation. Before, during, and after gamma radiation the thermoelectric voltage remained constant.

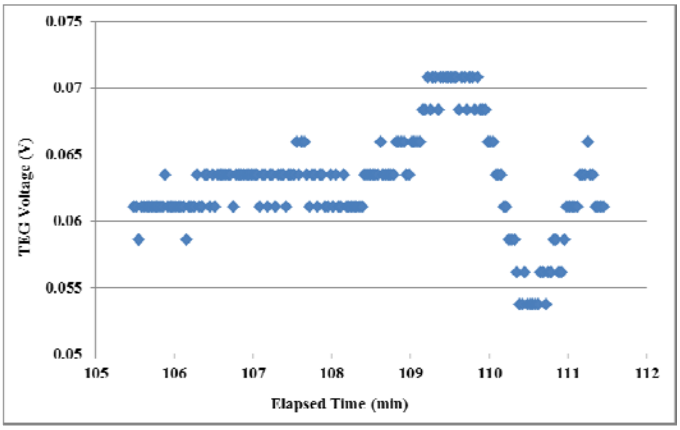

Fig. 7 TEG voltage after gamma irradiation vs. elapsed time

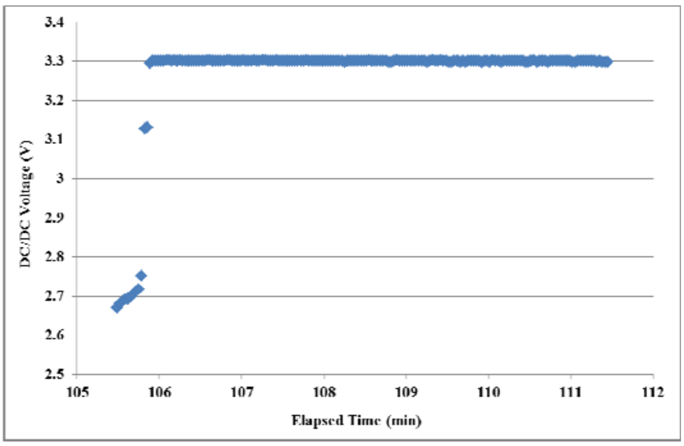

Fig. 8 DC/DC converter output voltage after gamma irradiation vs. elapsed time

As seen in Fig. 8 the DC/DC converter output voltage returned to its original pre-radiation value of 3.3 V after the ^{60}Co source was turned off and stayed constant.

The other important aspect to investigate is if the gamma radiation manifests itself in some type of signal noise in the transmission signal. To determine this, the RSSI and counter number will be compared before, during, and after gamma radiation. As seen in Table III there was no change in the RSSI value before, during, and after gamma radiation. This demonstrates that the transmitted power from the transceiver was constant during the experiment. Based on the one second transmission period and 45 minute collection period, 2700 signals should have been transmitted and collected. During the post radiation collection period, 360 counts should have been collected. From Table III only three signals were not counted before radiation. During gamma radiation all the signals were collected. After radiation only one signal was not counted in the six minute collection period. The presence of the gamma radiation did not adversely influence the transmission of the signal. The gamma radiation did not affect the signal strength or the number of collected transmission signals. It is unknown why the three signals before radiation and one signal after radiation were not counted during the experiment.

TABLE III COMPARISON OF ALL CASES

	No radiation	60Co radiation ($\dot{X}$=170.R/min)	End no radiation
Average TEG Voltage (V)	0.069	0.062	0.063
Standard Deviation of TEG Voltage (V)	0.008	0.004	0.004
Average DC/DC Voltage (V)	3.294	2.873	3.266
Standard Deviation of DC/DC Voltage (V)	0.006	0.155	0.138
Average RSSI	166	166	166
Standard Deviation of RSSI	0.325	0.400	0.281
Count Number Total	2697	2700	359

IV. CONCLUSIONS

A transceiver powered by a TEG and DC/DC converter can operate in a low gamma radiation environment. However, not all the electronic components are insensitive to its effects. The voltage produced from the TEG is unaffected by presence of gamma radiation. The gamma radiation should contribute to a heat generation source in the TEG. This gamma heating effect was taken into account in the modeling of the power production from the TEG. The transceiver is another electronic component that is unaffected by the gamma radiation. There was no change in the RSSI value before/during/after irradiation. Also, during gamma irradiation all the counts during the collection period were collected. So the presence of gamma radiation did not cause any signal noise. On the other hand, the DC/DC converter did exhibit different behavior during gamma radiation. During gamma exposure the DC/DC converter output voltage lost voltage regulation. The DC/DC converter output voltage decreased and oscillated by 0.7 V. This change in output voltages could be an issue because; if the voltage becomes too low, the transceiver will not be able to function. Transceivers require a certain operational voltage to function. For this experiment the DC/DC converter output voltage never dropped below 2.5 V. This is 0.5 V above the minimum operating voltage for these transceivers [15]. It is unclear what the relationship between the exposure rate and voltage oscillation is for this DC/DC converter. It is unknown if the voltage drop will increase with the increase in exposure rate at the start of the service life of the dry-cask and cause the output voltage to fall below a usable value. In the real system, the DC/DC converter should be constructed from radiation hardened electronics or the device should be properly shielded from the gamma radiation.

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